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The physical oceanography of the transport of floating marine debris

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Abstract

Marine plastic debris floating on the ocean surface is a major environmental problem. However, its distribution in the ocean is poorly mapped, and most of the plastic waste estimated to have entered the ocean from land is unaccounted for. Better understanding of how plastic debris is transported from coastal and marine sources is crucial to quantify and close the global inventory of marine plastics, which in turn represents critical information for mitigation or policy strategies. At the same time, plastic is a unique tracer that provides an opportunity to learn more about the physics and dynamics of our ocean across multiple scales, from the Ekman convergence in basin-scale gyres to individual waves in the surfzone. In this review, we comprehensively discuss what is known about the different processes that govern the transport of floating marine plastic debris in both the open ocean and the coastal zones, based on the published literature and referring to insights from neighbouring fields such as oil spill dispersion, marine safety recovery, plankton connectivity, and others. We discuss how measurements of marine plastics (both *in situ* and in the laboratory), remote sensing, and numerical simulations can elucidate these processes and their interactions across spatio-temporal scales.

1. Introduction

Plastic debris has rapidly become one of the most pervasive and permanent pollutants, particularly in marine ecosystems. It occurs in all compartments of the ocean worldwide, and has a range of adverse environmental and economic impacts. Although there are many critical environmental issues (notably linked to human population growth and the climate crisis, Stafford and Jones 2019), plastic pollution has attracted considerable attention in recent years, with numerous initiatives to tackle the problem from the United Nations, the G7 and G20, the European Commission and many national and local authorities, as well as non-governmental organisations.

The widespread nature of plastics in marine systems is generally assumed to result from their longevity in the environment (they degrade very slowly, mainly through mechanical abrasion and exposure to UV radiation) and relatively high buoyancy, which facilitates long-distance transport from source areas (Andrady 2005). By mass, roughly half of all plastics produced are less dense than seawater, and thus should float at sea (Geyer *et al* 2017). Many plastic items also contain trapped air (e.g. expanded polystyrene, intact bottles, buoys), which further increases their buoyancy and therefore increases windage, subsequently aiding their dispersal.

It is widely assumed that most plastic debris derives from land-based sources, mainly from densely populated continental areas, although some studies suggest (e.g. Bergmann *et al* 2017a, Lebreton *et al* 2018) that sea-based sources play an important role too. Nevertheless, there is a large mismatch between the estimates of the amount of municipal solid plastic waste generated on land that enters coastal waters (5–12 million tonnes yr^{-1}, Jambeck *et al* 2015) and the total amount of plastic floating at sea (less than 0.3 million tonnes, Cózar *et al* 2014, Eriksen *et al* 2014, van Sebille *et al* 2015b). Also, there is a discussion about whether the amount of plastics measured at sea over the last few decades (Lebreton *et al* 2019, Ostle *et al* 2019, Wilcox *et al* 2019) has kept pace with the growth in global plastic production (Goldstein *et al* 2012, Geyer *et al* 2017).

Taken together, these findings suggest that our understanding of plastic fluxes, pathways and fate is incomplete. Some of this discrepancy might be because our understanding of plastic fluxes is not complete, or because of the time delay between fluxes into the ocean and arrival in the regions where most measurements are taken (Lebreton *et al* 2019). But there are also a number of physical processes that may account for some of this discrepancy between estimates of plastic inputs and the pool of floating plastic at sea: beaching, sedimentation and fragmentation to sizes that have not been measured. There is evidence that the size and composition of large debris changes with distance from major land-based sources (Ryan 2015), possibly as a result of these mechanisms. Biological processes (e.g. ingestion or settlement) may also aid the (horizontal and vertical) transport of plastics within the oceans. In order to better address the plastic pollution challenge, we need a better understanding of the physical, chemical, and biological processes that influence the transport of plastics on the surface of the ocean.

With the growing attention on marine plastic debris by scientists and the public alike, there has been a plethora of scientific reviews in the last few years (e.g. Andrady 2011, Law 2017, Zhang 2017, Hardesty *et al* 2017a, Kane and Clare 2019, Maximenko *et al* 2019, Amaral-Zettler *et al* 2020, Hale *et al* 2020). However, none of these reviews focus exclusively on the physical processes that control the transport and the resulting distribution of plastic debris on all spatial scales, ranging from the ocean gyres to beaches. Here, we aim to provide a coherent and complete review of all these physical processes. We limit ourselves to the floating plastic debris, as most observations have been collected and theories developed for the dynamics of plastic at the ocean surface. Furthermore, the plastic at the surface of the ocean likely has the largest impact on marine life (e.g. Wilcox *et al* 2015, Compa *et al* 2019), and large debris (e.g. abandoned fishing nets) can also be navigational hazards (Hong *et al* 2017).

The objective of this review is not only to give an overview of the processes governing the dispersion of floating plastics, but also to highlight the opportunities to cross scales in physical oceanography by analysing floating plastics. Plastic is a unique tracer in that it is a solid material related to human activity with sources non-uniformly distributed along the world's coastlines, shipping lanes and fishing regions. Therefore, we hope that this review is of interest not only to oceanographers working on marine plastics, but also to physical oceanographers who aim to understand the way ocean processes interact across different scales (from basin-scale gyre circulation to individual waves). Note that, while we have assembled an author group with broad expertise, it is unavoidable that there are some biases because some expertise is better represented than others.

2. Methods on literature and data gathering

Plastic is a relatively new class of materials in the ocean. However, there is extensive literature on the transport and dispersion of other materials in the ocean which can supply a strong support to describe plastic transport. This literature includes natural particulates such as sea ice, sediment grains, macroalgae, wood and plants, pumice and a whole range of planktonic organisms from bacteria to *Sargassum* (Siegel *et al* 2003, Thiel and Gutow 2005). There is also much experience in prediction of transport for oil spills (e.g. Reed *et al* 1994, Fingas 2016, D'Asaro *et al* 2018) and in search and rescue (Breivik *et al* 2013, Zhang *et al* 2017), as well as theoretical work on the transport of material by oceanic Lagrangian Coherent Structures (e.g. Haller 2015). In this review, we analyse findings from these other fields, integrating fundamental classical works where appropriate with most recent investigations of leading research groups all over the world.

We identified key research questions in the field as well as relevant literature through three processes:

1. discussions with top scientists in the field at SCOR WG153 meetings in San Diego (USA) and Utrecht (NL) (www.scor-flotsam.it)
2. searching the web literature; and
3. asking colleagues around the world not included in the original SCOR group to provide us with references and written contribution. Scientists from all continents were involved.

The SCOR group drafted the very first outline provided by Stefano Aliani and Erik van Sebille further developed and assembled the text with the online contribution of all authors.

To obtain additional information we collected abstracts and chaired sessions on the topic of plastic pollution at most relevant international conferences worldwide in the last three years, including the Ocean Sciences Meeting 2018, the 6th International Marine Debris Conference, Micro2018, two IEEE Oceanic Engineering Society international workshops organized in 2018 and 2019 in Brest (France), the European Geosciences Union General Meeting, Ocean Optics XXIV, and the International Ocean Colour Science meeting. The authors are members of the most relevant global working groups on the topic, including AMAP, PAME, SAPEA and GESAMP and had access to topics and literature discussed therein.

3. Defining floating marine debris

Plastic debris items in the oceans vary widely in terms of size, shape or chemical composition. In this review paper, we focus specifically on *floating* plastic marine debris. That means that the plastic particles considered here are positively buoyant, i.e. their density is lower than the local water density. However, this does not mean that plastics remain at the sea surface at all times. Breaking waves and ocean turbulence can temporarily mix them down to several or even tens or hundreds of meters (Kukulka *et al* 2012, Poulain *et al* 2019), from where the particles ascend back to the surface after waves and turbulence decay. This tendency of particles to rise to the surface depends on the particle's terminal rise velocity (which, in turn, is also controlled by its shape and dimension) as well as on the density difference between plastic and sea water (Allen 1985, Chubarenko *et al* 2016). For example, for a given plastic density, the rise velocity generally increases as a function of sphere diameter.

As environmental plastic debris consists of mixtures of numerous particles and items, their sizes, densities and shapes can be represented by continuous distributions (Kooi and Koelmans 2019). Importantly, these plastic particle characteristics change continuously over time due to several processes (see also section 4) such as embrittlement, fragmentation, biofouling, weathering and erosion (e.g. ter Halle *et al* 2016). Some of these processes are not only physical or chemical, but also mediated by biological activity (Zettler *et al* 2013, Dawson *et al* 2018). Densities of the particles start from those of the parent polymer or product material density; however, because of the transformation processes listed above, particle densities measured from open ocean samples can range from 808 to 1240 kg m^{-3} (Morét-Ferguson *et al* 2010).

Furthermore, vertical mixing can affect the vertical distribution of both positively and negatively buoyant particles in the mixing layer (Kukulka *et al* 2012, Brunner *et al* 2015, Enders *et al* 2015, Reisser *et al* 2015,

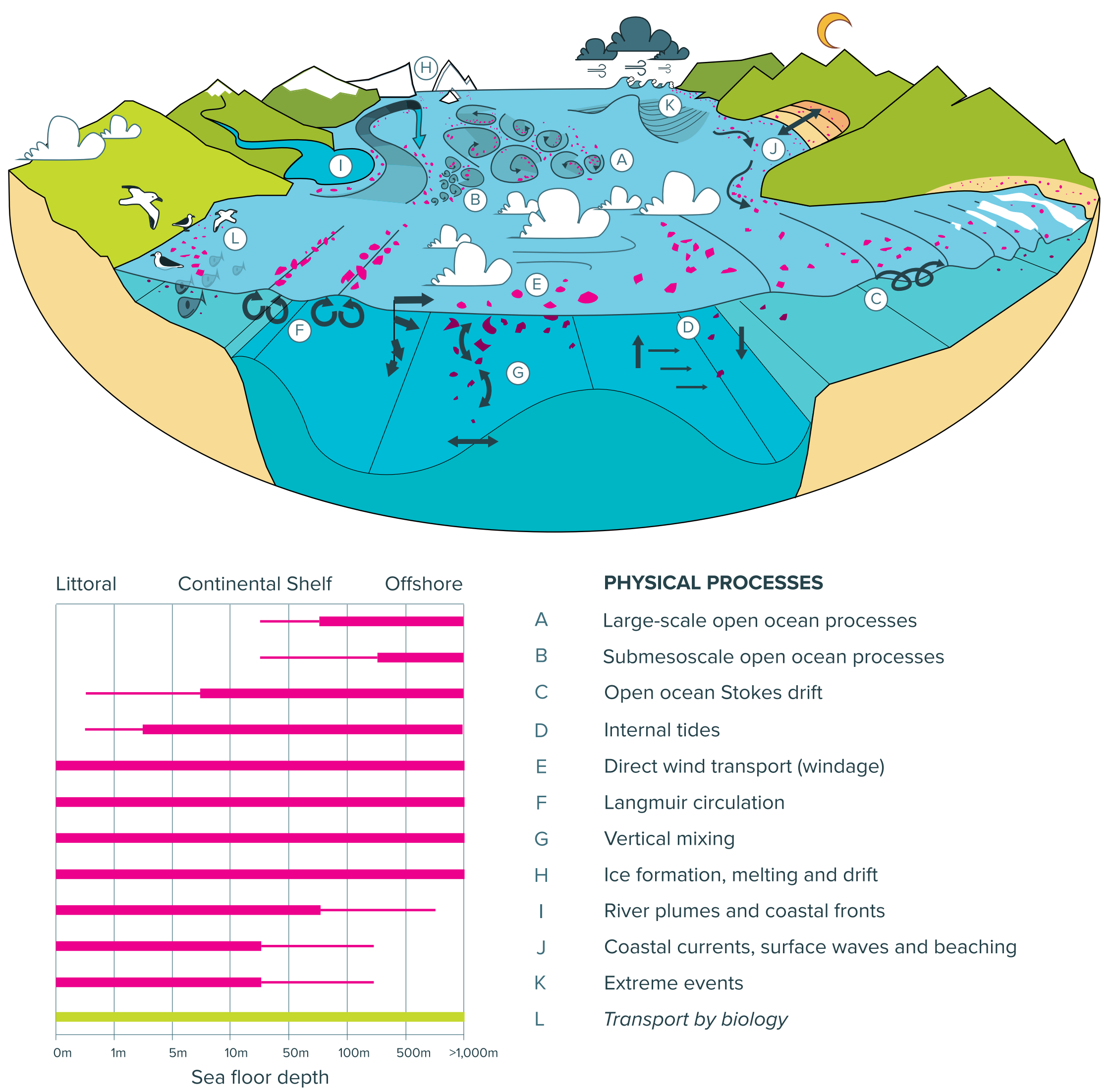

Figure 1. Schematic of the physical processes that affect the transport of plastic (pink items) in the ocean (top panel). The table (lower panel) identifies in which regions different processes are important. Thick pink lines in the table mean that the process is among the most important in that water depth, while thin pink lines mean that the process is only of secondary importance. Transport by organisms is not a physical process and therefore represented with a green line instead of a pink one.

Kooi *et al* 2017, Poulain *et al* 2019), which, in the presence of the vertical shear of ocean currents, can then also affect their horizontal dispersion (Wichmann *et al* 2019). Such differentiation of transport pathways determined by the vertical distribution of particles in the surface mixed layer was shown for oil droplets in oil spill modelling (Reed *et al* 1994, Röhrs *et al* 2018). Specific to plastics, it was shown that particle size and shape determine their orientation and movements under the influence of waves (DiBenedetto and Ouellette 2018) and inertia (Beron-Vera *et al* 2019).

Sizes of plastic particles discussed in this review range from 1 μm to 1 m. This very broad size range is often divided into different categories (microplastics, mesoplastics, macroplastics, megaplastics), but there is no community-wide agreement on where the boundaries between these categories lie. Here, we will not attempt to define such categories again, but rather we will use the nomenclature that is used within the respective papers. Shapes vary from very elongated shapes, such as fibres and ropes, to shapes with a lower surface area to volume ratio, such as fragments and spheroids (Ryan 2015).

4. The physical processes that govern transport of floating plastic debris

In this section, we will describe the different processes that govern the transport of floating plastics. These processes have been summarised in figure 1, in which we have schematically depicted where in the ocean these processes are most relevant, from the littoral zone to the open ocean. Transport here is defined loosely as any movement of plastic particles from one location to another in three-dimensional space. When modelling this transport, it is typically decomposed into a deterministic and a stochastic component, the latter accounting for (turbulent) mixing processes that

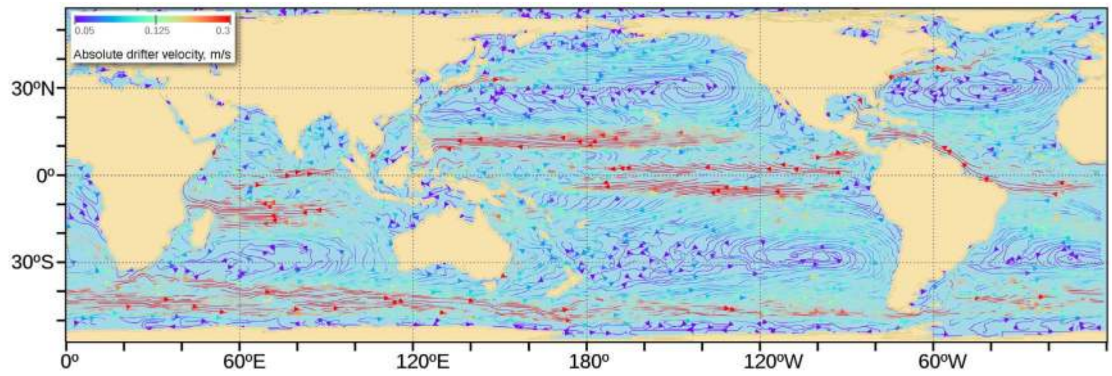

Figure 2. Schematic of large-scale ocean surface currents (gyres, convergence zones) based on mean velocities of undrogued surface drifters, with colouring indicative of speed. Floating plastic has been predicted and measured to accumulate in the centres of the five subtropical gyres, which can be seen in the figure as the points around which the drifters circulate centred at 30 degrees latitude in both hemispheres.

result from the unresolved part of the ocean currents, including wind and wave forcing fields varying randomly in space and time. Because of this stochastic component, it is more convenient in most cases to study particle transport with a large ensemble of plastic particles. Here, this ensemble transport is referred to as dispersion.

4.1. Large-scale open ocean processes

The horizontal large-scale flow is the most efficient way of transporting debris over large distances on the global scale, allowing connections between ecoregions and transport across basins. It is also the scale on which we know most about transport of floating plastics, partly because the Global Drifter Program that has been operational since the late 1970s is designed to measure this (Elipot *et al* 2016).

Large-scale physical oceanography is built upon geophysical fluid dynamics (Pedlosky 1987, Vallis 2006), a foundational theory well supported by ocean observations since the early 20th century. For the purposes of this review, large-scale circulation is driven by surface winds, generating so-called Ekman drift at the sea surface under the influence of the Earth's rotation, which is directed to the right of the wind in the Northern Hemisphere and to the left in the Southern Hemisphere. Ekman transport, integrated over the upper 10s of meters, creates regions of surface convergence and divergence, which in turn drive the large-scale geostrophic flow in the ocean interior. These areas of convergence are, on the large scale, found in all five subtropical gyres, which are basin-scale current systems defined by wind stress patterns and coastal boundaries (figure 2). Surface divergence, on the other hand, is found in the subpolar gyres and over parts of the Southern Ocean. Floating plastic items that do not experience waves (see section 4.4) or wind (see section 4.6) are transported by surface currents and will accumulate in areas where surface waters converge. In contrast, areas of divergence (outside of subtropical gyres) typically have lower concentrations of floating plastic (e.g. Maximenko *et al* 2012, Law *et al* 2014). In the basin-scale convergence regions, the surface water is pumped down (so-called Ekman downwelling) to depths of a few hundred meters. However, the downward vertical velocity of the water near the surface is typically much smaller (10 s of meters per year) than the rise velocity of buoyant plastic (Reisser *et al* 2015, Poulain *et al* 2019), so that the floating plastic stays behind.

This Ekman/geostrophy theory is remarkably capable of predicting the large-scale distribution of floating microplastic in the ocean (Kubota 1994, Martinez *et al* 2009, Onink *et al* 2019). This distribution reveals large-scale accumulation of plastics in the centres of the subtropical gyres in areas termed 'garbage patches'. Despite a persistent, common misconception of a 'garbage patch' as a giant floating island of trash (which do not exist), concentrations there are still fairly low. Based on field observations across the five subtropical gyres (Cózar *et al* 2014, Eriksen *et al* 2014, Law *et al* 2010, 2014), Cózar *et al* (2015) provided a more accurate description of the 'garbage patch', as large accumulation zones (millions of km^2 in area) dominated by tiny plastic pieces mainly on the order of millimeters, not easily perceptible by an observer on a ship. When the sea is calm, these plastic particles are present in nearly 100% of net surface tows in these areas, each covering around 1000 m^2, but the density of plastic pieces is not as high as the term 'patch' may suggest. The typical mean spatial concentration measured with net tows is around 1 plastic item in 4 m^2, reaching 1–10 items m^{-2} in the most polluted area. The accumulation zones in the subtropical gyres show high heterogeneity at multiple scales (e.g. Goldstein *et al* 2012, Brach *et al* 2018), and their borders are diffuse and changing. The gyres are not stationary in space nor static in time. Rather, the gyres, and with them the accumulation zones, change shape and move with time (Howell *et al* 2012, Lebreton *et al* 2018), and plastics are not trapped indefinitely in these gyres (van Sebille *et al* 2012a, Maes *et al* 2016).

While the large-scale open ocean processes can reasonably well explain the observed debris pattern (with some notable exceptions, e.g. in the North Atlantic accumulation zone, see also van Sebille *et al* (2015b), it is important to realise that these theories do not make any statements about the pathways and time scales of real plastic particles from sources into the open ocean accumulation zones. Furthermore, the vertical structure of near-surface currents (upper 10 s of meters, see also sections 4.4, 4.7 and 4.8) appears to have a considerable impact on the large-scale circulation patterns (Wichmann *et al* 2019), especially in the Indian and South Indian Oceans, where van der Mheen *et al* (2019) found that drifters drogued at 15 m depth give different accumulation patterns than undrogued drifters (see also Poulain *et al* 2009, Lumpkin *et al* 2012).

4.2. Mesoscale open ocean processes

Across the basin-scale gyre patterns, the ocean is full of eddies. Mesoscale eddies are slowly rotating vortices, with diameters of hundreds of kilometers (technically defined by the scale at which the Rossby number (e.g. Pedlosky 1987) is much less than order one), depths of few hundreds to thousands of meters and lifespans of weeks to years (Chelton *et al* 2011). Mesoscale eddies also form fronts and filaments between them by straining the surface waters; these fronts and filaments become unstable and in turn form submesoscale eddies, which are smaller and faster evolving than mesoscale eddies (1–10 km diameter, with lifetimes of days to weeks). Eddies exist in two types: cyclonic eddies (rotating counter-clockwise in the Northern Hemisphere, and clockwise in the Southern Hemisphere), for which the radial component of the surface flow is mostly outward; and anticyclonic, for which the radial component is mostly inward (note that the same is true for gyres, explaining the above convergence in anticyclonic subtropical gyres, and the divergence in cyclonic subpolar gyres). This inward surface flow for anticyclones could explain the observation that an anticyclonic eddy had more floating debris in its core than a cyclonic one (Brach *et al* 2018), although submesoscale eddies are more effective in accumulating debris (see section 4.3).

Nevertheless, the mesoscale eddies are certainly important, not only because they can retain debris, but also because the westward drift of these potentially long-lived structures can result in transport over thousands of kilometers, as has been shown for surface drifters (Dong *et al* 2011), as well as radioactive isotope markers (Budyansky *et al* 2015), plankton, jellyfish (Johnson *et al* 2005, Berline *et al* 2013), heat and salt (Dong *et al* 2014). The explicit consideration of mesoscale eddy variability has, for example, shown a convergent pathway of seawater connecting the South Indian subtropical region with the convergence zone of the South Pacific through the Great Australian Bight, the Tasman Sea, and the southwest Pacific Ocean (Maes *et al* 2018), as well as into the Atlantic Ocean via the Agulhas leakage (e.g. Beal *et al* 2011, van Sebille *et al* 2011).

Quasi-permanent jet-like features, commonly referred to as striations (Maximenko *et al* 2008, Belmadani *et al* 2017), may also play a role in the transport of floating plastics. Such small-scale structures are able to modulate the transport of surface material from the core of the convergence subtropical zones, revealing possible exit routes (Maes *et al* 2016). Such long distance pathways of dispersion represent a challenge for ocean modelling, and the exact role of mesoscale and submesoscale processes, as well as the relative importance of these processes in different ocean basins, are still not well known.

4.3. Submesoscale open ocean processes

In the last few decades, there has been increasing interest in oceanographic processes on scales smaller than a few tens of kilometers. Much progress has been made on describing, quantifying and developing a theory for these submesoscale features (Fox-Kemper *et al* 2011, Thomas *et al* 2013, McWilliams 2016). These submesoscale processes are known to be very important locally for drifters and *Sargassum* accumulation (Szekielda *et al* 2010, Pearson *et al* 2019), as well as oil spills transport and dispersion (Zhong and Bracco 2013), as they systematically increase mixing (Poje *et al* 2014, McWilliams 2019).

Particularly relevant to how floating plastic particles are affected by submesoscale processes was the finding in D'Asaro *et al* (2018) that flotsam accumulates at density fronts and in cyclonic vortices (as opposed to the anticyclonic mesoscale eddies). The mechanism that causes this accumulation in cyclonic vortices is complicated, but is related to vortex stretching of the submesoscale vortices. In eddies, the frontogenesis and secondary radial-overturning circulation that cause surface convergence depend on the Rossby number. These processes are considerably stronger at the submesoscale than at the mesoscale for the same level of kinetic energy per unit area (e.g. Rascle *et al* 2017). Although often revealed from high-resolution satellite imagery (e.g. Kudryavtsev *et al* 2012), these submesoscale processes are typically not resolved even in 'high-resolution' models.

4.4. Open ocean Stokes drift

During its periodic motion, a particle floating on the free surface of a surface gravity wave experiences a net drift velocity in the direction of wave propagation, known as the Stokes drift (Stokes 1847). More generally, the Stokes drift velocity is the difference between the average Lagrangian flow velocity of a fluid parcel and the average Eulerian flow velocity of the fluid (see van den Bremer and Breivik (2018) for a review). Fluid parcels are followed in the Lagrangian reference frame, whereas in the Eulerian framework fluid motion is described at fixed spatial locations. Stokes drift arises due to the fact that particles subject to a surface wave field move forward at the top of their orbits faster than backward at the bottom and spend longer in crests where their velocity is positive than in troughs where their velocity is negative.

Surface gravity waves on the open ocean are mostly caused by winds. For this reason, it is often assumed that any net transport carried by waves can be parameterised as a fraction of the wind speed in the same direction as the wind (Weber 1983). However, waves are slower to build to strength and are more persistent than winds, and, once they have evolved into swell waves, they can travel long distances with low dissipation (Ardhuin *et al* 2009a, Hanley *et al* 2010, Webb and Fox-Kemper 2015). Thus, the waves at a particular location and time may have been caused by earlier winds at another location. Wave models, such as WAM and WaveWatch-III (Tolman 2009), were developed to predict the propagation and strength of waves, and can therefore be used to predict Stokes drift.

Even though Stokes drift is a second-order effect (in the generally small steepness of the waves), whose magnitude is much less than the magnitude of the wave orbital motions themselves, the magnitude of the Stokes drift is frequently significant (McWilliams and Restrepo 1999). Either empirical wave spectra for fully-developed waves (Pierson and Moskowitz 1964, Hasselmann *et al* 1976) or the output of wave models can be used to accurately predict the Stokes drift (Webb and Fox-Kemper 2011, 2015) under the assumption of weak surface slope. The simplification of monochromatic waves at the peak wave period, commonly adopted in Eulerian ocean models, leads to a Stokes drift that decays exponentially with depth, although alternative parameterisations have been proposed that more accurately capture the depth profile for realistic spectra (Breivik *et al* 2016). For realistic waves, the Stokes drift is strongly surface-intensified, decaying faster than exponentially for a typical spectrum (Webb and Fox-Kemper 2011, 2015). From an observational perspective, Stokes drift can be inferred from high-frequency radar (Ardhuin *et al* 2009b) and has the potential to be estimated from satellite measurements (Ardhuin *et al* 2019). It can be accurately measured in the laboratory (e.g. van den Bremer *et al* 2019).

Whether floating marine plastic particles are actually transported with the velocity of their surrounding Lagrangian flow (and thus with the Stokes drift) and whether particles of all shapes, densities and sizes are transported at the same speed under similar conditions remain open questions. Objects that are submerged, small and of the same density as the surrounding fluid will travel with the Lagrangian flow (Maxey and Riley 1983). For fully submerged particles that have a different density from the surrounding fluid, it has been shown (Eames 2008, Santamaria *et al* 2013) that their inertia can cause lighter (and thus upward settling) particles to be transported more rapidly than the Stokes drift of the surrounding fluid and vice versa for heavier (downward settling) particles. Furthermore, the response of particles to eddies and turbulence may also be different (Maxey and Riley 1983). The shape of the particles determines their orientation under waves but not necessarily their transport velocity (DiBenedetto and Ouellette 2018). For very steep waves, particles may surf on the wave (Pizzo 2017) or be subject to transport faster than the Stokes drift due to wave breaking (Pizzo *et al* 2019).

Floating objects are subject not only to Stokes drift but also to motions with longer time scales (e.g. geostrophic flow), as well as windage (see section 4.6). Observations of these different transports independently are rare (e.g. Ardhuin *et al* 2009a). Despite the poorly understood complexity in the relationship between Stokes drift and transport of floating material, Stokes drift is one of the key components of many simulations of the drift of floating marine plastic particles. Different authors have considered its effects on different types of objects: for example, Stokes drift can make a significant contribution to the trajectories of drifters (Röhrs *et al* 2012, Meyerjürgens *et al* 2019); it must be accounted for in search and recovery missions (e.g. the crashed airplane MH370; Trinanes *et al* 2016, Durgadoo *et al* 2019); and it can be key in the local modelling of oil spills (Christensen and Terrile 2009, Drivdal *et al* 2014). In addition to transport, a random wave field and its associated random Stokes drift field have the capacity to disperse or 'diffuse' a cloud of floating tracers (Herterich and Hasselmann 1982), but this effect is generally small, local and dominated by other sources of dispersion (Herterich and Hasselmann 1982, Spydell *et al* 2007).

In an early study focusing on debris accumulation near Hawaii, Kubota (1994) found that Stokes drift did not significantly contribute to debris transport, but only took into account Stokes drift derived directly from the local wind fields and not swell. A number of recent modelling studies took into account Stokes drift from the entire wave field, combining wind and swell waves, and found a greater role for Stokes drift. In the Sea of Japan, Stokes drift moved plastic particles between 5 and 10 mm towards the Japanese coast during winter (Iwasaki *et al* 2017). A similar effect was found in the Norwegian Sea (Delandmeter and van Sebille 2019). Stokes drift can also lead to leakage of particles out of the Indian Ocean (Dobler *et al* 2019) and can cause drifting particles to cross the strong circumpolar winds and currents and reach the Antarctic coast (Fraser *et al* 2018). On a global scale, Stokes drift does not per se contribute to large-scale accumulation of microplastics in the subtropics, but does lead to an increased transport to polar regions where storm-generated waves are larger and occur more frequently (Onink *et al* 2019).

As the Stokes drift depends strongly on the shape of the waves (it is proportional to the square of their steepness), rapid changes in the waves can lead to rapid changes in particle transport. This plays a role in the coastal zone, where waves steepen and ultimately break (see section 4.11), and during storms, when waves rapidly steepen and the Stokes drift rapidly increases. This change is crucial for plastic debris beaching: developing steep stormy waves may 'grab' plastics and sediments from the beach, and transport these offshore; whilst smoother waves, which remain after the wind ceases, slowly return plastics and sediments back to shore (Chubarenko and Stepanova 2017).

Finally, it cannot be emphasized enough that the Stokes drift and the Eulerian currents do not evolve independently. Two effects need to be distinguished. First, a realistic ocean is not made up of regular waves, but the broad-banded spectral content of its waves leads to a group-like structure. For wave groups, the net positive transport associated with the Stokes drift becomes divergent on the group scale and is accompanied by an opposing Eulerian return flow at depth (Longuet-Higgins and Stewart 1962, Haney and Young 2017). In the open ocean, this return flow is very small and will not have any significant effect on the transport of floating plastics (van den Bremer and Taylor 2016).

Second, there are important connections between the Stokes drift and the Eulerian currents through the Stokes forces (Hasselmann 1970, Craik and Leibovich 1976, McWilliams *et al* 1997, Ardhuin *et al* 2007, Lane *et al* 2007, Polton and Belcher 2007, Suzuki *et al* 2016). While the dynamical details of these interactions exceed the goals of this paper, it is sufficient to note that, at leading order, there is often an important *anti-Stokes* response of the Eulerian current to the presence of Stokes drift, and such an anti-Stokes flow has been observed *in situ* in coastal areas (Lentz and Fewings 2012). This tendency for the Eulerian flow to oppose the Stokes current is caused by the Stokes forces that connect the Stokes drift to the Eulerian currents, primarily the Stokes-Coriolis and Stokes advection terms. If these forces are unbalanced, then effectively a net force from the waves is applied to the Eulerian currents until they oppose the Stokes drift. This effect recasts the standard large-scale geophysical fluid dynamics problems to include Stokes effects: wavy Ekman layers (McWilliams *et al* 2012), wavy geostrophic fronts and filaments (McWilliams and Fox-Kemper 2013), and wavy hydrodynamic instabilities (Haney *et al* 2015). On large scales, the consequence is that the net *Lagrangian* transport (combining the Stokes and Eulerian currents) behaves much like the traditional large-scale transport theory predicts: Ekman layers and geostrophic currents driven by Ekman convergence. The anti-Stokes response explains how Stokes advection by itself can cause a larger impact than Stokes advection plus other Stokes forces (Breivik *et al* 2015). On the mesoscale and submesoscale, the Stokes vortex and Stokes shear forces become important (McWilliams and Fox-Kemper 2013, Suzuki and Fox-Kemper 2016), which can influence frontogenesis, instabilities, and turbulence (Haney *et al* 2015, Suzuki *et al* 2016) and indeed leads to a further reinforcement of the anti-Stokes effect (Pearson 2017). On smaller scales, the Stokes vortex and shear forces play a major role and lead to Langmuir circulations and Langmuir turbulence.

In regards to the transport of plastics and other pollutants by Stokes drift, one must be careful to consider the forces of interaction between the Stokes and Eulerian flows. In a modelling context, this means simultaneously solving a wave model and an ocean transport model with the correct coupling between them. Models that explore this are e.g. COAWST (Warner *et al* 2010), SWAN + ADCIRC (Dietrich *et al* 2012) and UWIN-CM (Curcic *et al* 2016, Li *et al* 2018). Exploring the consequences of such coupled modelling for the transport of marine debris will be one of the most important challenges ahead.

4.5. Internal tides

The movement of the tides over banks, reefs, and the continental shelf break generates large internal waves generated by internal tides (Kao *et al* 1985, Hibiya 1990). Surface convergences moving with these waves have been demonstrated to concentrate and transport larval invertebrates, fish and tar balls from an oil spill (Shanks 1983, 1987, 1988). The most common site for the generation of these internal waves is the continental shelf break. As the tide ebbs off the shelf, a lee wave or hydraulic jump is produced over the continental slope. When the tide changes to flood, this lee wave propagates up onto the shelf and shoreward where it evolves into a train of internal waves. As the waves move into shallow water they can break forming an internal (underwater) bore (Cairns 1967, Winant 1974, Pineda 1995).

Surface currents are generated over the internal waves (Shanks 1995). Over waves of depression (the nonlinear wave has a trough but no crest), the surface current is in the direction of wave propagation. At the surface over the leading edge of the wave, the surface current turns downward forming a surface convergence, which moves along with the wave. Over larger waves of depression the surface current can be as fast or faster than wave propagation and, under these conditions, objects at the surface, for example surface-oriented larvae or buoyant flotsam, are carried into the convergence, concentrated there and transported along with the internal wave (Shanks *et al* 2000).

Waves generated at the shelf break may cause transport across the shelf. Where waves are generated over a bank, they can propagate over deep water for long distances, e.g. large internal waves are generated over the Pearl Bank in the Sulu Sea and propagate across the basin hitting the coast of Palawan Island (Apel *et al* 1985). In the Caribbean, internal waves are formed around Trinidad and Tobago and propagate northward (Giese *et al* 1990). In the Mediterranean, they are formed over the Camarinal Sill at the Strait of Gibraltar (Bruno *et al* 2002).

Convergences over sets of internal waves are visible from space in both visible and synthetic aperture radar (SAR) images (Apel *et al* 1975, Alpers 1985). When winds are light, convergences appear as slicks of smooth water; oils in the surface film are transported into the convergence dampening capillary waves. Often floating material, algae and flotsam, become concentrated and transported along with the waves. Each wave of a set can generate a surface slick. Similar to surface waves, tidally generated internal waves are refracted by the bottom topography; hence, the surface slicks tend to be oriented parallel to bottom contours. Sailing perpendicular to a set of waves, convergence zones appear as long (100s of meters) slicks oriented parallel to the bottom contours with distances separating the slicks on the order of 100s of meters. The edges of the slicks are sharply delineated. This set of features is characteristic of tidally generated internal waves and can be used as a diagnostic tool to identify their surface expression (Shanks 1983).

4.6. Transport due to direct wind force (windage)

Windage is the effect of wind on items with a freeboard, i.e. an area protruding out of the water. While the wind-induced displacement velocity may be directly related to the wind speed (Tapia *et al* 2004, Astudillo *et al* 2009), it is important to realise that windage does not correspond to the portion of surface flow field driven by the wind, which is already contained in the surface current, but to the direct wind drag exerted on items at the sea surface (Zambianchi *et al* 2014). In practice, the effects of windage and Stokes drift (at least that of the locally wind-driven waves) are typically combined, and the so-called 'leeway' is defined as the wind and wave-induced motion of a drifting object relative to the ambient current (Richardson 1997, Kako *et al* 2010, Breivik *et al* 2011).

Ignoring its Stokes drift component, windage results from the combination of a skin drag and a form drag forces (e.g. Petty *et al* 2017). Skin drag results from the viscous friction on the surface of the object exposed to the wind. Form drag arises because of the wind pressure on the part of the object above the sea surface. The latter depends quantitatively on the buoyancy ratio (the ratio between the cross-sections of floating objects normal to the wind direction above and below the sea surface), which in turn depends on both the density and shape of a floating body (Zambianchi *et al* 2014, Ryan 2015). This aspect may be very relevant for floating marine debris, as it might be responsible for sorting plastics with different buoyancies and sizes. This affects their wind drag coefficient (Chubarenko *et al* 2016, Pereiro *et al* 2018) and hence their dispersion (Aliani and Molcard 2003), ultimately affecting both residence time and beaching characteristics of floating items (Yoon *et al* 2010). Model simulations of Maximenko *et al* (2018) of drifting debris generated by the 2011 tsunami in Japan have been validated using observational reports, and demonstrated that 'high-windage' objects crossed the North Pacific in less than a year and were relatively quickly pushed from the ocean onto the North American coastline, while heavy, low-windage debris collected in the mid-basin convergence zone.

4.7. Langmuir circulation

In some circumstances, the surface flow can attain the form of coherent roll structures: pairs of counter-rotating vortices aligned horizontally. The most well-known flow of this type is the Langmuir circulation (Langmuir 1938), which can be recognised by the formation of windrows.

Windrows are common and clearly identifiable features of the surface ocean. They are lines of bubbles and surface debris generally aligned with the wind that are the visible surface manifestation of the convergence zones between wind-wave-induced, counter-rotating, wind-parallel helical vortex pairs referred to as Langmuir circulation (figure 3). Planktonic organisms also accumulate in Langmuir circulation cells, potentially enhancing the biofouling of flotsam, as well as increasing the likelihood of accidental entanglement in, and ingestion of, plastic items by more mobile predators due to the close proximity between plastic and biota (Gove *et al* 2019).

The formation of Langmuir cells is the manifestation of the interaction between the wind-induced shear flow and the wave-induced Stokes drift (Craik 1977, Leibovich 1977, 1980). It can be shown mathematically that shear flow becomes unstable in the presence of vertically sheared Stokes drift. Small perturbations in the downwind flow lead to the formation of downwind-directed rolls, so that water parcels describe spiral trajectories. Langmuir circulation cells generally occur under wind speeds greater than 3–5 m s^{-1}, and their formation and/or re-formation takes only about a few minutes (Thorpe 2004). Alternate cells, which can be kilometers long, rotate in opposite directions, causing formation of lines with converging and diverging surface flows associated with downwelling and upwelling, respectively, beneath these lines. The water in the cells also moves downwind, so that motion is helical.

Convergence and divergence zones in Langmuir circulation are difficult to spot over the water surface (Faller 1964), but become visible when there is foam or flotsam on the surface accumulated by the convergence. After only 15–20 min of wind action, floating material can already be accumulated in stripes, and is

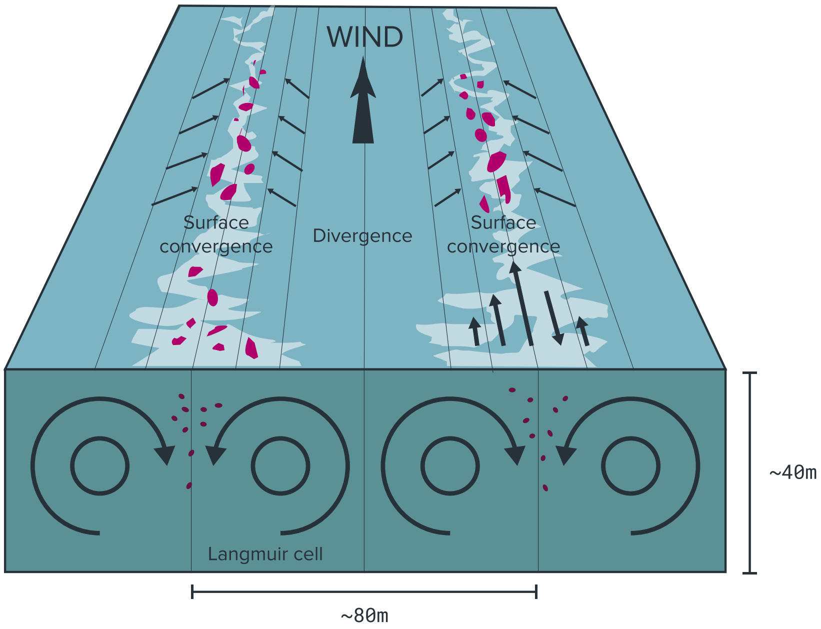

Figure 3. Schematic of Langmuir circulation and water dynamics therein. Pink particles are plastic particles, which accumulate in regions where Lagmuir cells converge at the surface. Adapted from Dethleff *et al* (2009).

kept there as long as the particular row persists (Chang *et al* 2019). Over time, the cells become larger and merge together, leading to the formation of Y-junctions at the surface (Thorpe 2004, Marmorino *et al* 2005), pointing generally down-wind in deep waters or equally up- and down-wind in shallow areas (Chubarenko *et al* 2010). The lifespan of Y-junctions is only 2–5 min, after which the regular structure of windrows is re-established.

Even when windrows may not be apparent or are highly disordered, the vertical velocity magnitude of near-surface turbulence can be enhanced by the presence of Stokes forces, a condition known as Langmuir turbulence (McWilliams *et al* 1997, McWilliams and Sullivan 2000, D'Asaro *et al* 2014). Because of the close connection between vertical velocities and surface convergence, the disordered windrows may still participate in the active accumulation of surface material on horizontal scales of 10s to 100s of meters (Carlson *et al* 2018).

Langmuir circulations, submesoscale fronts, internal waves, and other related roll-like instabilities with surface convergence (van Roekel *et al* 2012) may explain occasional observations from ships of extremely high concentrations of floating debris ordered in 2–3 m wide stripes that stretch to the horizon (Faller 1964, Barstow 1983, Law *et al* 2014, Carlson *et al* 2018). These parallel windrows were seen in the centres of the gyres under low-wind conditions; however, the exact census of the dynamics forming them is incomplete, and their frequency of occurrence is poorly constrained observationally. However, climate models that parameterise Langmuir turbulence and submesoscale fronts and eddies predict them to be globally ubiquitous (Fox-Kemper *et al* 2011, Li *et al* 2016).

The relatively strong vertical flows in Langmuir circulation may remove smaller items from the surface, especially when the buoyancy of plastic particles is small compared to the vertical current (Brunner *et al* 2015, Kukulka and Brunner 2015). Observed vertical profiles of microplastics concentrations are only consistent with turbulence-resolving simulations if Langmuir circulation is explicitly included in the model (Brunner *et al* 2015). Submesoscale structures, such as strong fronts, can play a similar role (Smith *et al* 2016, Suzuki *et al* 2016, Taylor 2018). Sampling of microplastics from nets that only skim the surface may underestimate abundance in areas of divergence or overestimate in areas of convergence.

Non-neutrally buoyant particles (whether sinking or rising) in a laminar, near-surface flow will describe closed elliptic trajectories within a 'zone of retention' under the water surface (Stommel 1949), and the combination of these coherent structures and turbulence will tend to homogenise the particles across the retention zone (Farmer and Li 1994). For positively buoyant particles there are two qualitatively different behaviours (Bees *et al* 1998): some particles are trapped in closed orbits at some distance below the surface (the Stommel retention zone), whereas others accumulate at the line of convergence at the fluid surface. In the absence of any other transport or diffusive processes, buoyant particles that begin at the surface cannot submerge and, hence, will not enter the Stommel retention zone no matter how fast the fluid flow is in the Langmuir circulation. It is rare to find such circumstances, however, as waves and the occasional whitecapping or breaker typically coexist with Langmuir turbulence. Analysis of forces (the buoyancy force and the dynamic pressure force) acting on particles (Dethleff *et al* 2009, Chubarenko *et al* 2010), shows that particles recirculate, describing different retention trajectories depending on particle size and density (see also Woodcock 1993). Thus, Langmuir turbulence inter-mixes particles near the surface of the ocean by forcing particles with different buoyancy to follow different paths.

Stokes drift, Langmuir circulation, and the buoyancy of marine debris also influence the horizontal dispersion of buoyant material in the ocean surface layer (Colbo and Li 1999, Kukulka and Veron 2019). Horizontal dispersion is driven by vertically sheared horizontal mean currents and turbulent velocities. Less buoyant material is mixed throughout the ocean boundary layer (which is about 10–100 m deep), so that dispersion by shear is predominant, whereas more surface-trapped (but still fully submerged) buoyant particles are dispersed by turbulent currents (Liang *et al* 2018).

Realistic ocean models where Stokes drift has been included (Warner *et al* 2010) show significant improvements in regions where wave-current interactions are strong. On the other hand, Langmuir circulation and turbulence are not commonly included explicitly in regional or global ocean models, although recent software developments in GOTM (Umlauf and Burchard 2003) and CVMix (Griffies *et al* 2015) may make using parameterisations of Langmuir turbulence easier (Li *et al* 2019). In idealised settings, Langmuir turbulence has led to improvements in parameterisations of vertical mixing in the boundary layer (McWilliams and Sullivan 2000, Kantha and Clayson 2004, Harcourt 2012, Noh *et al* 2015), which could form the basis for stochastic parameterisations of three-dimensional transport of particles (e.g. Holm 2015).

4.8. Vertical transport and mixing

The vertical distribution of floating plastic depends not only on the particle's buoyancy, but also on the dynamic pressure due to vertical movements of ocean water. Understanding of the vertical flow in the ocean is challenging because it is induced by several processes acting at different temporal and spatial scales. It can exist as coherent structures such as large-scale (Ekman) pumping, upwelling and downwelling, fronts, and turbulence-induced roll structures such as convection cells and Langmuir circulations. Wave-enhanced turbulence is also present without large-scale features (e.g. Kukulka *et al* 2012). There can also be vertical mixing in estuaries and river mouths, but in the presence of strong stratifications and tidal motion, the vertical mixing of plastics is much more complex there (see sections 4.10 and 4.11). The typical scales of these processes in the open ocean are presented in table 1, ranked from highest to lowest averaged vertical velocity.

Diurnal heating of the ocean surface layer also influences near-surface vertical mixing processes. Strong surface heat fluxes result in diurnal warm layers with near-surface density gradients (Price *et al* 1986, Soloviev and Lukas 1997, Plueddemann and Weller 1999). Such density stratification suppresses turbulence and associated near-surface mixing (Li and Garrett 1995, Min and Noh 2004, Kukulka *et al* 2013). Turbulence-resolving large-eddy simulations indicate that turbulent downward fluxes of buoyant tracers are suppressed in heating conditions, so that buoyant material is surface-trapped, which is consistent with microplastics observations in the Atlantic and Pacific Oceans (Kukulka *et al* 2016).

Measured rise velocities for various types of plastics and size classes typically range in the order of millimetres to 10s of centimetres per second (Reisser *et al* 2015, Lebreton *et al* 2018, Poulain *et al* 2019), which places the rise velocity right in the middle of the range of vertical velocities typical of boundary layer turbulence and the submesoscale (Taylor 2018) in table 1. It may also be important to take into account the effect of the positively-buoyant particles sized around the Kolmogorov micro-scale (Ruiz *et al* 2004, Cózar *et al* 2014), and the dynamics of flow around suspended particles (Maxey and Riley 1983). It is worth noting here that the vertical dispersion of buoyant particles in the water column has been studied in the past, for example, in the context of frazil ice dynamics (Svensson and Omstedt 1998), algal blooms (Moreno-Ostos *et al* 2009), and diurnal vertical migrations, and that lessons could be learned from these case studies.

4.9. Ice formation, melting and drift

The poleward migration of floating plastics from highly populated latitudes to polar regions has been reported in the Northeastern Atlantic sector of the Arctic Ocean (Lusher *et al* 2015, Bergmann *et al* 2016, Cózar *et al* 2017), and the central Arctic Ocean (Kanhai *et al* 2018). Once there, floating plastic takes part in the cycles of formation and melting of the sea ice. Observations show (Obbard *et al* 2014, Peeken *et al* 2018a, 2018b) that Arctic sea ice has microplastics concentrations that are several orders of magnitude higher than that in the water column. Sea ice has already been identified as a major means of transport and redistribution for sediments (Nürnberg *et al* 1994, Gregory *et al* 2002); various pollutants and contaminants in polar regions (Pfirman *et al* 1997, Rigor and Colony 1997, Korsnes *et al* 2002), including oil spills (Blanken *et al* 2017); as well as microplastics (Peeken *et al* 2018b).

As with other particles, plastic particles become concentrated in sea ice during ice formation through a process known as scavenging (figure 4), which concentrates particles by 1–2 orders of magnitude relative to ambient seawater (Obbard *et al* 2014). Even though this phenomenon has not yet been investigated for plastics specifically, the details of the process probably

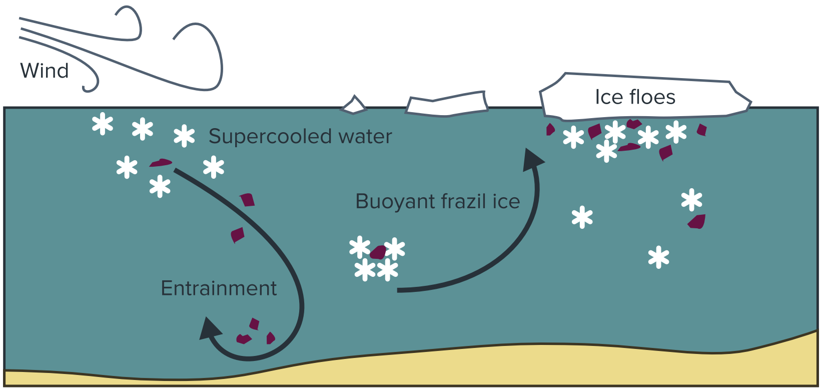

Figure 4. Schematic of how freezing of frazil ice captures and entrains plastic particles. Figure by Anneke Vries, based on Daly (2008).

Table 1. Characteristic vertical spatial scales and averaged vertical velocities for different open ocean processes inducing vertical transport.

	Vertical spatial scale	Averaged vertical velocities
Langmuir circulation	Related to mixing layer depth or Stokes drift decay depth (Wang *et al* 2018), typically between 5 and 50 m (Thorpe 2004).	Typically a few cm s^{-1} and up to 20 cm s^{-1}, increases with wind and Stokes drift (Leibovich 1983, Weller *et al* 1985, Harcourt and D'Asaro 2008)
Vertical mixing induced by breaking waves	<10 m (Sullivan *et al* 2007), related to significant wave height (Terray *et al* 1996)	Typically 5 cm s^{-1} (Sullivan *et al* 2007)
Convective cells	10–1000 m	Typically 2–4 cm s^{-1} in coastal seas and 2–12 cm s^{-1} in polar deep ocean convection (Stommel *et al* 1971, Schott and Leaman 1991, Gawarkiewicz and Chapman 1995, Lavender *et al* 2002)
(Submesoscale) Fronts	Around 40 m (D'Asaro *et al* 2018)	Typically 1 cm s^{-1} (D'Asaro *et al* 2018, Taylor 2018)
Ekman pumping	10s to 100s of metres	10s metre yr^{-1} (=few μm s^{-1}) (Johnson *et al* 2001)

depend on the shape, size and density of plastic particles. As ocean water cools to the freezing point (and slightly below it), small needle-like ice crystals form (typically 3 to 4 mm long; called frazil ice). These crystals consist of nearly pure freshwater, releasing salt into the surrounding sea water. At this stage, both thermal and haline convection develops in the upper water layer, sometimes to depths of several metres (Lake and Lewis 1970, Ushio and Wakatsuchi 1993, Peterson 2018). The frazil crystals are usually suspended in the top few centimetres of the surface layer of the ocean, but can be stirred to a depth of several metres by wave-induced turbulence (Omstedt 1985, Svensson and Omstedt 1998). With further cooling, the growing number of floating frazil crystals aggregate and freeze together, leading to the formation of grease ice (a soupy layer on the surface), then slush and shuga (behaving like a layer of a viscous fluid, a few cm across), then nilas (elastic crusts up to 10 cm thick), then pancake ice (typically up to 10 cm in thickness, 30 cm–3 m in diameter). Brine releases during the growth of the ice, and vertical (thermal plus haline) convection supports further mixing, transporting suspended particles to the upper water layers. This way, both floating and slightly-negatively buoyant plastic particles could come into contact with newly-freezing ice needles and thus be captured into the ice.

In contrast to freezing, melting of sea ice takes place at the air-sea interface. This provides a certain 'lifting' mechanism for the (plastic) particles under freeze/thaw cycles: being captured by growing ice from below, they become closer to the surface as the ice melts.

Sea-ice can also transport plastic particles laterally. Therefore, sea-ice movements can be used to track the movement of trapped plastics (Peeken *et al* 2018b). Instruments such as passive microwave satellite images combined with the motions of sea ice buoys have been used to study sea ice drift patterns (Tschudi *et al* 2010, Tekman *et al* 2017). Understanding these dynamics is especially important in the context of future trends towards thinner sea ice and ice-free summers, and changes in the extent of ice-free areas, ice movement patterns in polar regions and resulting changes in ocean circulation transport. Changes caused by the shift from multi-year ice extent to first-year ice might result in the tendency of sea ice floes to diverge from the main drift pattern such as the Transpolar Drift (Szanyi *et al* 2016), with complex effects on exchange processes of any contaminants between the Exclusive Economic Zones of the various Arctic nations (Newton *et al* 2017).

4.10. River plumes and coastal fronts

Large rivers can move plastic debris originating on land out to sea (Lebreton *et al* 2017, Schmidt *et al* 2017). In (sub-)polar regions, this can be exacerbated seasonally by melting of riverine ice in spring, carrying previously ice-locked plastics to sea (Holmes *et al* 2012). In river plumes, the river water and ocean water are in direct contact, forming fronts that may persist for 10s or 100s of kilometres into the open ocean. Plume fronts are often visible from large distances (including from space) due to the contrasting optical properties of these water masses (Acha *et al* 2015). At estuarine fronts, distinct differences between the water masses can be observed, typically with the lighter freshwater at the surface extending farther out to sea, and the denser seawater below intruding farther upriver.

Floating objects (both natural and anthropogenic) tend to accumulate at these fronts for similar reasons as for the submesoscale frontogenesis processes described above, which is reflected in higher debris abundance along the outer river plume edge (Atwood *et al* 2019), as well as on the seafloor and on the shore (Acha *et al* 2003). River plumes may also contribute to the accumulation of floating debris on seashores downstream of contaminated rivers. Microplastic beaching rates have been shown to depend strongly on the characteristics of the river mouth (Atwood *et al* 2019), and seashores downstream of the river outflow had higher densities of anthropogenic debris than seashores upstream or distant from river mouths (Rech *et al* 2014, Cheung *et al* 2016). Finally, coastal fronts, whether generated by river plumes, upwellings, or by other processes, may also block the transport of floating items, including marine plastics (Hinojosa *et al* 2011, Garden *et al* 2014, Ourmieres *et al* 2018). As has been shown for sediments, nutrients and Persistent Organic Pollutants (POPs), river mouths and coastal zones can act as physico-chemical barriers, or filters, retaining and modifying a certain part of the flux of the material towards the ocean (e.g. Emelyanov 2005). Enhanced flocculation of clay and organic matter in areas of contact of riverine and marine waters may also favour the retention of floating plastic objects.

4.11. Coastal currents, surface waves and beaching

The dominant hydrodynamics in coastal waters that control the transport of plastic particles differ significantly from the hydrodynamics occurring in the open ocean. The complex 3D circulation patterns controlling plastic transport on the onshore side of the inner shelf region are largely influenced by wind, waves and tides, with the relative importance of forcing depending on water depth (Lentz and Fewings 2012). Tidal currents generate turbulence near the bottom (Trowbridge and Lentz 2018). In estuaries, tides and density fields also interact in complex ways, for example resulting in converging fronts or particle trapping (MacCready and Geyer 2010). The coastline morphology and its interaction with the hydrodynamics also impact particle transport and, due to the shallowness of the water, even horizontal transport of floating plastics is influenced by the seafloor.

The presence of the seabed results in a substantial nonlinear evolution of the waves from their deep-water state (Elgar and Guza 1985). The shape of individual shoaling waves changes from an almost symmetrical profile in deep water to a shape with sharp crests and broad, flat troughs in coastal waters (Elgar and Guza 1985, Doering and Bowen 1995). This increase in steepness has important implications for the strength of the Stokes drift (see section 4.4). Furthermore, as ocean surface gravity waves move from offshore regions to coastal waters, they start to feel the seabed and some of the wave energy is dissipated by friction, resulting in a thin boundary layer. Within this layer, the horizontal and vertical orbital velocities are not exactly $\pi/2$ out of phase, resulting in a net horizontal wave Reynolds stress acting in the direction of wave propagation, known as boundary layer streaming (Longuet-Higgins 1953), which acts in addition to the Stokes drift.

The wave asymmetry increases until the waves become unstable and eventually break. Wave breaking enhances the Lagrangian drift close to the surface (Deike *et al* 2017, Pizzo *et al* 2019). The enhanced turbulence due to wave breaking increases mixing, which can cause resuspension of particles from the seabed (Deigaard 1993). Broken waves propagate further in the inner surf zone until they reach the shoreline, where they collapse and climb up and down the beach face in the swash zone. The transport of plastic in the swash zone depends on plastic buoyancy and swash zone flow asymmetry (Hinata *et al* 2017). Large floating particles that are seaward of the shoreline but within a distance of approximately half of the run-up length are susceptible to beaching (Baldock *et al* 2008). Particles with low settling velocity are recaptured by small eddies (with diameters of centimeters to meters) induced by swash waves and then transported seaward, while large particles with high settling velocities remain in the swash region (Hinata *et al* 2017). This obviously has impacts on the residence time of plastic close to the beach face. Plastic particles washed ashore by large waves will deteriorate at rates that depend on weathering history and residence time on the beach, and fragment into small pieces that can be backwashed offshore by swash waves and wave-induced nearshore currents (Isobe *et al* 2014, Kataoka and Hinata 2015).

The wave evolution and dissipation also induces currents, which are three-dimensional, and their influence can be separated into a cross-shore component (perpendicular to the coastline) and a longshore component (parallel to the coastline). Waves approaching the coastline at an angle result in a net longshore current that moves particles along the coast (Longuet-Higgins and Stewart 1962, Taffs and

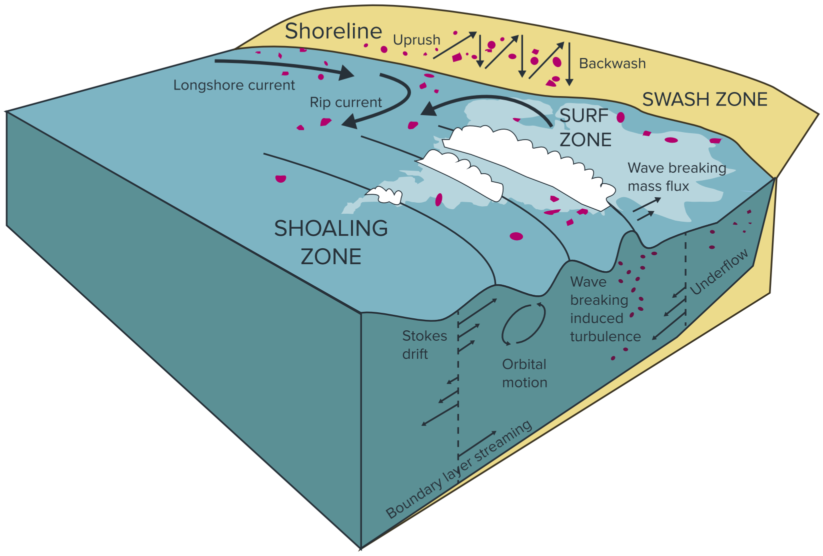

Figure 5. Schematic of the processes that transport plastics in the coastal zone. Adapted from figure 1.2 of van der Zanden (2016).

Cullen 2005). In the cross-shore direction, an offshore-directed mean velocity, termed the mean return flow or undertow, exists within the surf zone as a result of a vertical imbalance between the wave-induced momentum flux (radiation stress) and the pressure gradient generated by the mean water surface slope (Svendsen 1984).

Buoyant plastic particles are affected more by the onshore drift as they have a tendency to remain at the sea surface, whereas small plastic particles are more likely to be mixed into the water column and follow the undertow offshore (Isobe *et al* 2014, Kataoka and Hinata 2015). As evidence of this, more floating plastic bottles were found inside the surfzone than outside it in an observational survey in the southern Mediterranean (Pasternak *et al* 2018). Other studies describing zooplankton accumulation have also reported a correlation between the position of the plankton community in the water column with onshore transport due to surface Stokes drift or bottom streaming and offshore transport in the mid-water-column undertow (Shanks *et al* 2015). Furthermore, because of this vertical variation in the horizontal mean velocity, beach morphology influences the direction of transport: more dissipative beaches tend to trap plankton inside the surf zone, while reflective beaches keep the plankton outside the surf zone (Morgan *et al* 2017).

A particularly relevant wave-induced current is the rip-current, which is a seaward-directed current that originates within the surf zone, expands outside the breaking region and can extend to the inner shelf (see figure 5). Rip-currents eject surf zone water onto the inner shelf and are potentially an important channel for seaward transport of plastic particles. Rip-current systems can trap floating material within the surf zone, as the surf zone currents move particles toward the centre of the rip (MacMahan *et al* 2010, Fujimura *et al* 2014).

There is still surprisingly little literature on the processes that control how plastic and other buoyant pollutants, such as oil, beach. Attempts have been made to create data-driven estimates of litter on beaches, where beach litter categories are predicted over time using artificial neural networks, using data of large debris on beaches from cleanup surveys (e.g. Balas *et al* 2004, Schulz and Matthies 2014, Granado *et al* 2019). Another approach is based on the fact that natural sorting and retention of certain type of sediments (sand, granules, pebbles) are observed on coastlines (Reniers *et al* 2013). The same could be happening with plastic particles: beach characteristics like steepness and sediment type could determine which particles get stranded (Hardesty *et al* 2017b). For example, surface roughness and the pore size of the beach sediments are likely to be important when plastic objects are pushed on the shore by the wave run-up.

Finally, coastlines are also considered to be hotspots for microplastic generation (Andrady 2011). Degradation of plastic appears to be related to ultraviolet radiation and/or mechanical abrasion by sediments (Song *et al* 2017) and fragmentation in the sea swash and wave breaking zone, especially during storm events (Chubarenko and Stepanova 2017, Chubarenko *et al* 2018, Efimova *et al* 2018). The fragmentation rate of beached plastic might be closely related to the residence time on beaches (Kataoka and Hinata 2015, Fanini and Bozzeda 2018) and is dependent on polymer type (Song *et al* 2017) and temperature (Andrady 2011).

4.12. Extreme events

While extreme events such as floods, tsunamis and storms are known to play an important role in the release of plastic and other materials into the ocean (e.g. Thiel and Haye 2006, Axelsson and van Sebille 2017, Gündoğdu *et al* 2018, Hurley *et al* 2018, Maximenko *et al* 2018), very little is known about how these phenomena affect the transport of floating marine plastic debris. Some information about the arrival of debris flushed out to sea during the 2011 Japan tsunami onto shores of North America and Hawaii is provided by Carlton *et al* (2017). There is evidence that storms significantly affect the transport of floating items in the North Sea (Stanev *et al* 2019). However, not much more has been reported in the literature at present.

4.13. Transport by organisms

Organisms can also transport plastic debris, either after ingestion or entanglement. Examples are plastic particles moved by seabirds to breeding colonies (e.g. Buxton *et al* 2013, Le Guen *et al* 2020). Transport to land by birds takes several routes, including predation (e.g. Ryan and Fraser 1988) and regurgitation to chicks (Ryan 1988), which may either die ashore or regurgitate plastic and other indigestible prey remains prior to fledging (Lavers *et al* 2018), thereby effectively transporting plastic. Migrating animals can also ingest and excrete plastic, thereby redistributing it (e.g. Rummel *et al* 2016). Furthermore, biota have a large role in moving floating plastic from the sea surface to depth (see section 5), and may also cause fragmentation through biting or grinding occuring during digestion.

5. How plastic particles sink from the ocean surface

It is generally accepted that the seabed is a sink of plastic debris (Van Cauwenberghe *et al* 2013, Woodall *et al* 2014, Corcoran 2015). While sinking towards the seafloor is rather obvious for initially negatively-buoyant objects, which imminently start to settle upon entering the marine environment, there is substantial evidence of positively buoyant particles in the water column and in marine sediments (Bergmann *et al* 2017b, Song *et al* 2018). Sedimentation of initially buoyant (or floating) marine debris occurs as a result of various transformation processes listed below. Note that the first four of these processes are relevant only for the small-scaled plastic particles, typically micro- and nano-plastics.

(1) Plastic particles might become entrained in or stick to so-called marine snow (organic detritus) to form sinking aggregates. Regional *in situ* observations reveal that up to 70% of analysed marine snow aggregates contained microplastic (Zhao *et al* 2018, de Haan *et al* 2019). Laboratory experiments show that incorporation into artificial marine aggregates strongly enhances the sinking velocity of plastic, reaching sinking velocities of several hundred metres per day (Long *et al* 2015, Michels *et al* 2018, Porter *et al* 2018). Agglomeration of nano- and microplastic particles may be facilitated by exopolymeric substances (Summers *et al* 2018) and biofilm formation on the plastic surface (Michels *et al* 2018).

(2) Plastic particles might be incorporated into sinking fecal pellets. Microplastics are known to be ingested by plankton, fishes, seabirds and marine mammals, and part of the ingested debris ultimately is packaged into fecal pellets (Lee *et al* 2013, Cole *et al* 2015, 2016, Katija *et al* 2017). Not only does this incorporation in fecal pellets significantly increase the settling velocity of plastic particles, the plastic can also significantly alter the structural integrity, density, and sinking rates of fecal pellets egested by marine zooplankton (Cole *et al* 2016).

(3) Plastic particles might be carried with the 'plastic pump' by giant larvaceans (Katija *et al* 2017), zooplankton (Sun *et al* 2018), and mesopelagic fishes such as lantern fishes, myctophids and others (Boerger *et al* 2010, Choy and Drazen 2013, Lusher *et al* 2016). These are among the most abundant pelagic groups in our oceans and, through their vertical migrations, are known to rapidly transport carbon and nutrients to the deep sea (Wieczorek *et al* 2018). Feeding near the surface at night and migrating to depths during the day, they might be responsible for the transport and removal of large quantities of microplastics from the surface ocean to the deep sea (Lusher *et al* 2016, Sun *et al* 2018, Choy *et al* 2019).

(4) Plastic particles may aggregate with suspended inorganic particles such as clay, and therefore increase in density and sink, as was shown experimentally for nano-sized polystyrene spheres (Besseling *et al* 2017). In polar regions, sea-ice derived (cryogenic) gypsum could potentially serve as an effective ballast mineral for microplastics in the same way as shown by Wollenburg *et al* (2018) for *Phaeocystis* aggregates.

(5) Plastic buoyancy may be affected by biofouling (Kooi *et al* 2017). Epibionts growing on plastic particles add mass and, depending on the organism's specific density, cause changes in overall buoyancy of the fouled particle (Zettler *et al* 2013), increasing settling velocity (Kaiser *et al* 2017). These effects are more important on particles with large surface area to volume ratios that have lower initial buoyancy (Ryan 2015) and can rapidly lead to sinking of fouled particles (Fazey and Ryan 2016).

(6) Plastic particles may be transported by hyperpycnal flows, typically generated by flash floods

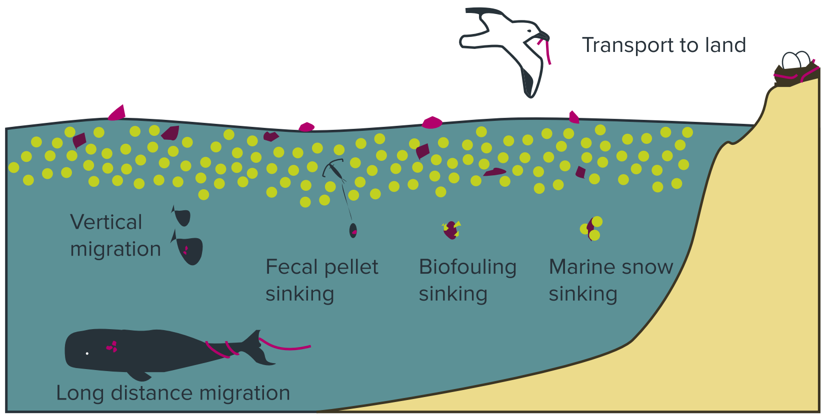

Figure 6. Schematic of the different transport processes by which organisms can affect movements of initially buoyant plastics. Green circles represent plankton.

(Pierdomenico *et al* 2019) or deep-water cascading events (Sanchez-Vidal *et al* 2015, Tubau *et al* 2015). Once the debris is funnelled into submarine canyons, it may be further re-mobilized by sedimentary gravity flows triggered by storms, floods or earthquakes.

While all of these processes have been observed in the lab or in the field, their relative importance is generally unclear between different regions of the ocean (figure 6). For example, it could be hypothesised that microplastic sedimentation primarily happens in the regions of high productivity such as river plumes or upwelling zones. On the other hand, zooplankton-plastics encounters would be more probable in oligotrophic waters since plastic to plankton ratios are higher there, leading to the (unverified) hypothesis that plastic ingestion is more common in oligotrophic oceans. The spatial distribution of vertical transport processes is a large knowledge gap.

6. The tools to investigate transport processes

6.1. *In situ* measurements

The transport of floating marine plastic particles can be investigated with the aid of Lagrangian observations. Recently, Langrangian observations have been derived from satellite-tracked drifters (Elipot *et al* 2016) and have contributed to the description of the dynamics of 'garbage patches' in the Atlantic and Pacific Ocean (Maximenko *et al* 2012, van Sebille *et al* 2012a). Zambianchi *et al* (2017) used trajectories of more than 1400 surface drifters to describe retention times of floating marine debris in the Mediterranean Sea. Drifter experiments have improved the understanding of physical processes related to motion of aquatic floating objects (e.g. Carlson *et al* 2016, 2017). Several studies analysed the pairwise dispersion of drifters to estimate mixing regimes and diffusivities from submesoscales and mesoscales to larger scales (Koszalka *et al* 2009, Poje *et al* 2014, van Sebille *et al* 2015a, Corrado *et al* 2017). The understanding of these processes is very valuable for the accurate parameterisation of turbulent diffusivities in particle tracking models (e.g. Christensen *et al* 2018). D'Asaro *et al* (2018) showed with surface drifter experiments that floating materials can concentrate at density fronts and that oil spills, for instance, could increase in thickness by a factor of 10^4 in convergence areas. Examination of where surface drifters end up on the shore (e.g. Lumpkin *et al* 2012) can help to understand coastal sinks of floating debris.

The transport of drifters on the ocean surface is highly influenced by the windage and thus by size, shape and buoyancy of the drifters. The windage depends on the drag area ratio of the drifter, which is defined by the cross-sectional area below the water surface divided by the cross-sectional area above the water line that is directly exposed to the air. The very popular Surface Velocity Program drifter design, which uses subsurface drogues to minimize the direct wind drag, typically has a drag area ratio around 40 and is primarily used for investigating complex surface current systems (Lumpkin *et al* 2017).

Drifter designs that focus on transport and dispersion of pollutants like floating marine debris or oil spills typically have a lower drag area ratio and target the transport in the upper metre, taking into account wind- and wave-induced motions. A recent observational study shows a strong near-surface current shear in the upper metre of the water column that implies that larger plastics are primarily transported by these wind- and wave-induced motions (Laxague *et al* 2018). Some of the most recent drifter designs have adjustable drag area ratios to simulate different floating objects with different characteristics, and can continue transmissions while being beached and recaptured (Meyerjürgens *et al* 2019, Stanev *et al* 2019). Other novel drifters are extremely low-tech (e.g. bamboo plates), but are designed to be tracked in high resolution from cameras mounted on aerostats (Carlson et al 2018).

In situ horizontal and vertical samples of plastic particles on various spatial and temporal scales can provide data on the plastic distribution and properties such as morphology, density and size. It is important to note that any particular sampling design (e.g. plankton nets, bulk water sampling, visual surveying, etc) measures only a portion of the particle size spectrum, which spans nanometers (albeit not yet measurable in nature) to tens of meters in size. Parameterisations that correct the microplastic density in surface measurements based on the wind field and sea state have been developed (Kukulka et al 2012).

Additional field observations, including samples recovered from marine biota, can be used to evaluate biological interaction such as biofilm, aggregation, and fecal pellet formation, ingestion and vertical migration, and their geographical distribution and relative contribution to the vertical transport of plastics. These data are especially important as input for and validation of numerical models (Kooi and Koelmans 2019, Poulain et al 2019), discussed in section 6.4 below. Field experiments to investigate the transport of floating plastic with actual (micro)plastic itself are challenging, especially in the deep ocean. However, there is at least one good example of a field experiment in the coastal zone (Hinata et al 2017). Short-term experiments with surface drifters in coastal waters can also provide useful information about drift trajectories and velocities (Astudillo et al 2009). Temporal deposition dynamics were studied through the assessment of new versus old plastic pellets on a Mediterranean beach (Fanini and Bozzeda 2018). Given the growing interest in the topic from the experimental coastal community, we expect more of such field experiments in the future.

The different types of *in situ* measurements yield different data, that are often not easy to compare or combine. Hence, Maximenko et al (2019) recently proposed the development of an Integrated Marine Debris Observation System, where strategies and methodologies are developed to integrate the different measurements, including also remote sensing data (see section 6.3 below).

6.2. Laboratory experiments

Laboratory experiments can help us understand many aspects of the behaviour of marine plastic debris in the ocean and validate parameterisations before they are used in large-scale ocean models, including their transport by waves, beaching, vertical mixing and the resulting vertical distribution, abrasion, and fragmentation. The laboratory is a well-controlled environment and, consequently, it is possible to focus on a specific process and properly describe its influence on plastic transport. It is imperative in these experiments, as is common in physics, to present results in a non-dimensional way, introducing non-dimensional numbers such as the (particle) Reynolds number, the Stokes number, the Langmuir number, and the Schmidt number. Only then can insights from the laboratory be applied to the ocean.

Exemplary laboratory measurements on floating plastic transport are the experiments relating to the wave-induced Stokes transport (reviewed in van den Bremer and Breivik 2018), with more recent contributions examining very steep non-breaking waves in intermediate depth including boundary layer streaming (Grue and Kolaas 2017), wave groups in deep water including their Eulerian return flow (van den Bremer et al 2019), and the orientation of non-spherical particles (DiBenedetto et al 2019). Although the behaviour of infinitesimally small, neutrally buoyant submerged particles in small-steepness non-breaking waves is well understood, laboratory experiments offer ample scope to improve our understanding of the transport of floating particles of different sizes, shapes and density in different water depths in steep and breaking waves.

Laboratory experiments also present a useful tool to study the motion of plastics in the nearshore environment, including plastic beaching. Detailed information on surf and swash zone hydrodynamics and the motion of sediment particles can be obtained experimentally (Alsina and Cáceres 2011, van der Zanden et al 2017), with potential influence on the motion of lower-density plastic particles. Laboratory experiments have also provided measurements of the advection scale of neutrally buoyant particles from the inner surf to the swash zone (Baldock et al 2008), which is the spatial scale relevant to the beaching of plastic particles. However, further experiments are needed to fully characterize this beaching and the influence of different variables such as beach configuration, sediment size, particle size, and density. The beaching of plastic particles is important to understand the marine plastic cycle and it is often introduced in parametric form in numerical models (e.g. Jalón-Rojas et al 2019). To study plastic beaching, laboratory measurements should be complemented with field observations and measurements. Challenges in measuring plastic beaching in the laboratory arise from the need for accurate wave generation and control of the mean Eulerian flows, and resulting vorticity in the laboratory flume or basin, which depend on laboratory-specific conditions (e.g. Monismith et al 2007, van den Bremer et al 2019). Equally challenging is the accurate tracking of particles in a highly turbulent and bubbly environment, such as the surf and swash zones. Video cameras have been used for Stokes-drift-type experiments, where accurate measurements are needed, as the net motion in every period is small compared to the periodic orbital motions themselves. Measuring the beaching of plastic particles requires even longer measurements and greater spatial coverage than previous experiments (i.e. from the inner surf zone to the maximum run-up).

The role of wave-induced transport cannot be assessed, nor can estimates of the total amount of plastic in the ocean be made without understanding its vertical distribution. As previously mentioned, one of the key parameters that controls this vertical distribution is the particle rise/settling velocity. The parametric expression for this velocity, a balance between the drag and the buoyancy forces, is known for regular shapes, such as spheres, disks, and ellipsoids (Clift *et al* 1978, Leith 1987), though it is less-well understood for irregularly shaped particles. This approach—widely used in sedimentology—was verified experimentally in fluid at rest for plastics between 1 and 5 mm with regular shapes (Waldschläger and Schüttrumpf 2019) and for smaller particles (Khatmullina and Isachenko 2017, Kaiser *et al* 2019). However, plastics have random and ragged shapes and Poulain *et al* (2019) developed a tool to predict upper and lower bounds for rise velocity for particles of sizes between 1 and 5 mm. The dynamics of fibres or very small plastics, on the other hand, remains poorly documented, and overall the interaction between particles and turbulence is a major knowledge gap in a realistic description of the vertical distribution of plastics in the ocean. More experiments are also needed to parameterise the influence of plastic degradation and biofilm formation on the rise/settling velocity (Kaiser *et al* 2017). The vertical distribution is also influenced by particle concentration, through affecting the turbulence (Bennett *et al* 2013), and size (Bennett *et al* 2014). Experiments have yet to be carried out to quantify the effects of these characteristics on floating plastics. Recently developed optical techniques, especially in four dimensions, could be useful in the context of plastic transport, and these new tools could also be useful to study the coupling between vertical mixing and horizontal transport.

Laboratory experiments are also needed to measure how particles on the coastal seafloor get resuspended back to the surface. The resuspension threshold controls at which shear stress (applied by the current just above the bed) a particle is captured and transported by the flow (Chubarenko and Stepanova 2017). The applicability of thresholds from the sedimentology literature is a matter for further study, as plastics (even when accounting for their different densities compared to sediments) are present in a variety of one, two or three-dimensional shapes. Moreover, sedimentological studies generally have a different goal: they mainly address the problem of bed erosion, searching for the beginning of rolling/saltation/sheet-flow motions of particles covering the entire bed (Shields 1936, Bagnold 1955). For plastics, the problem is different: plastic particles in the ocean are re-suspended from the bed covered by sediments with different properties (grain size, density, shape, water content). This means that the same plastic particle will have different motion threshold on different sediment types. On a rough bed, where the plastic particle size is less than the sediment grain size, the threshold becomes dependent on particle orientation to the flow, requiring statistical approaches to threshold quantification. In addition, bioturbation may lead to retention and burial of particles into deeper sediment layers (Iribarne *et al* 2000, Soltwedel *et al* 2019). Thus, laboratory approaches and theoretical formalism developed in sedimentology need to be adjusted to answer specific questions regarding the re-suspension of plastic particles.

Biological interaction is one of the key mechanisms to remove floating plastics from the sea surface and transport them to the water column, deep sea and sea floor (section 5), and the removal rate of floating (micro)plastics is an important input parameter for horizontal transportation models (section 6.4). However, removal rates due to biofilm formation, aggregation, fecal pellet sinking, ingestion and vertical migration are not well parameterised yet. Laboratory microcosm and outdoor mesocosm experiments on short and long time scales are thus required in various biological and environmental conditions with (micro) plastics of different morphology, size and polymer type to determine the removal and vertical transportation rates.

While the abrasive wear and resulting life time of synthetic polymers is usually tested by industry under the conditions they are designed for, these tests do not generally include unintended environments like the ocean, nor lifetimes beyond the intended duration of use of these materials. Consequently, the abrasive wear of plastics under conditions of repeated mixing with natural beach sediments is only known for modelling carried out in laboratory experiments. For example, laboratory experiments have been used to quantify the mechanical abrasion and fragmentation of plastic particles in the swash zone where waves repeatedly run up and run down on shoreface sediments (Efimova *et al* 2018, Chubarenko *et al* 2020) or in water (Resmeriţă *et al* 2018). As is common in experiments on the abrasive wear of materials, the next step for marine plastics is to obtain statistics. The methodology is effective, simple, cheap, and robust even though quite laborious, and can be extended to more types of plastics, with different sediments and sediment mixtures, to examine the influence of solar radiation, temperature, and other key factors expected to be important. The latter should be checked at both high and low (environmentally-relevant) temperatures, because the properties of plastics change quite significantly, from high plasticity on tropical beaches to brittle in polar ice (Lancaster 1969).

6.3. Remote sensing

Remote sensing using sensors mounted on satellites, high altitude pseudo-satellites, aircrafts, unmanned aerial systems, ships, fixed platforms or handheld sensors can generate geophysical and chemical proxy information about optically active targets from a distance. To this end, prospective application of remote sensing tools to understand the dynamics and pathways of plastics can be performed (i) directly by using optical, radar sensors as well as visual inspection, and (ii) indirectly by inferring relevant distribution information based on observations of other Essential Ocean Variables (Mace 2012, Garaba and Dierssen 2018 and references therein). At present, most progress in the direct remote sensing of plastic has been made in the field of optical remote sensing operating in the visible (350 nm) to shortwave infrared (2500 nm) spectrum. Direct applications and scientific progress involving optical remote sensing for detecting, quantifying, classifying and tracking floating plastic debris, has recently been reviewed in Maximenko *et al* (2019) and Martinez-Vicente *et al* (2019). The two main approaches that have been widely implemented in analyses of imagery include automated image/object recognition and spectral analyses.

Plastic debris can be identified using visual recognition, either by trained observers (e.g. Garaba *et al* 2018) or by automated processing of digital imagery developed through machine learning (e.g. Martin *et al* 2018). The current suite of satellite missions has varying geo-spatial and spectral capabilities (Garaba and Zielinski 2015, Greb *et al* 2018). In terms of geo-spatial capabilities, Maxar Technologies WorldView missions can produce imagery with a pixel size of ~0.3 × 0.3 m. Although this is very high-resolution imaging, distinguishing individual particles has not been fully achieved using captured imagery.

The other approach builds on the science of optical remote sensing and the unique spectral reflectance of plastics. The key end-product of ocean colour remote sensing is reflectance, the ratio of light reflected from the ocean surface and incident light (Nicodemus *et al* 1977). Ocean colour remote sensing has been very successful in monitoring water quality parameters such as concentrations of algae, dissolved organic matter and suspended particles through their optically active properties. Recent studies have reported promising findings suggesting the potential detection and identification of floating and slightly submerged plastic debris using optical sensing in the visible to short wave infrared spectrum (Garaba and Dierssen 2018, Garaba *et al* 2018, Goddijn-Murphy and Dufaur 2018, Goddijn-Murphy *et al* 2018, Topouzelis *et al* 2019). However, it has been very challenging to detect microplastics submerged in the water column because water strongly absorbs light in the infrared wavelengths that characterize plastics.

It has become clear that spectral remote sensing would improve by using complementary measurements based on different sensing technologies (Maximenko *et al* 2019). Manned and unmanned platforms equipped with LIDAR and thermal infrared (TIR) imaging have potential applications in the remote sensing of floating plastic debris (Girard-Ardhuin *et al* 2005, Pichel *et al* 2012, Veenstra and Churnside 2012, Topouzelis *et al* 2019). TIR remote sensing measures the surface emissivity of the ocean and routinely provides sea surface temperature estimations. For directly measuring plastic debris on top of the water surface, Goddijn-Murphy and Williamson (2019) expect it to work best at locations where the air-sea temperature difference is largest. Because TIR radiance is strongly absorbed in water, it cannot sense suspended microplastics. Passive microwave sensing also measures the surface emissivity of the ocean, but in the microwave region of the electromagnetic spectrum. Measurements, commonly expressed as brightness temperature, relate to sea surface properties like temperature, salinity and roughness.

Active microwave sensors (which emit microwaves and measure the back scatter) have not yet demonstrated the capability to detect plastic debris directly, but provide information that aids in the identification of potential debris convergence points and pathways. Surfactants, man-made and natural, accumulate in surface current convergence zones, where debris will also accumulate (D'Asaro *et al* 2018). These surfactants modify surface tension and, hence, the Bragg waves responsible for radar scattering, and show as darker ocean patches in radar imagery. These dark patch signatures in SAR data have been used successfully to monitor oil spills (Fingas and Brown 2014) and provide candidate areas for debris accumulation. The radar altimeter constellation measures ocean surface heights, from which geostrophic currents products are generated and distributed operationally by the Archiving, Validation and Interpretation of Satellite Oceanographic data data distribution site at http://aviso.oceanobs.com. These geostrophic currents have been used to identify ocean fronts and filaments, where debris may accumulate, by means of the geostrophic current field Lyapunov exponents (e.g. Nencioli *et al* 2013).

Radar scatterometers provide global high resolution (12.5 km) wind speed and direction data which may be used to estimate Ekman currents (Dohan and Maximenko 2010), and which are used to generate estimated surface current products, such as OSCAR (Bonjean and Lagerloef 2002). Scatterometer derived winds may also be used to estimate windage and have been shown to have significant skill in predicting Stokes drift (Clarke and Gorder 2018). Finally, in recent years, the technology to measure surface currents directly using Doppler scatterometry have been demonstrated using airborne and spaceborne sensors (Chapron *et al* 2005, Romeiser *et al* 2010, Kudryavtsev *et al* 2012, Rodríguez *et al* 2018). These advances have resulted in proposals for future space missions to measure surface currents and winds (WaCM, Rodríguez *et al* 2019), surface currents and waves (SKIM, Ardhuin *et al* 2019), or high-resolution surface currents, winds and waves (SEASTAR, Gommenginger *et al* 2019), which may add significant skill in predicting the pathways for man-made debris dispersal.

Thermal infrared sensors, altimeters, scatterometers, passive microwave as well as visible spectrum sensors are all used to study sea ice. The potential for microwave remote sensing to directly observe floating plastic debris has not yet been exploited. However, all aforementioned observations of the ocean surface can help predict pathways, locations and distribution of floating ocean plastics. Satellite observations are essential to complement numerical simulations in locating fronts (e.g. Rascle *et al* 2014), eddies, gyres and plumes, sometimes through tracking surfactants (Munk *et al* 2000), making it possible to identify potential zones of accumulation in the open ocean. An overview of satellite remote sensing for studying physical processes at the ocean surface is given by Shutler *et al* (2016).

6.4. Numerical simulations

Most of our knowledge about the distribution of ocean plastic comes from simulations of the transport of plastic particles with numerical models. Given the sparsity of observations, numerical simulations can be used to both 'fill in the gaps' between these observations, and to test hypotheses about how plastic particles behave in the ocean. See Hardesty *et al* (2017a) for an extensive review on how numerical model simulations can be used to improve the understanding of microplastic distribution and pathways.

There are essentially two complementary approaches that can be used to simulate plastic transport. The first is the Eulerian framework, which is commonly used in sediment simulations (e.g. Michallet and Mory 2004, Chauchat 2018), for example. On a global scale, plastic can be simulated within these Eulerian models as a tracer, somewhat similar to how other tracers such as temperature and salinity are treated (Mountford and Morales Maqueda 2019).

The Eulerian framework is also used in a one-dimensional setup, for example, to estimate the turbulence-corrected concentration from plastics measurements at sea (Kukulka *et al* 2012, Enders *et al* 2015, Poulain *et al* 2019). These Eulerian models solve a set of two-phase equations on a grid: the fluid phase, and the particle phase through the particle concentration. The vertical mixing is modelled by a turbulent diffusivity parameterisation that takes into account the turbulence source (through the eddy viscosity) and the particle-fluid coupling (through the turbulent Schmidt number). The value of this Schmidt number is an open question (Tominaga and Stathopoulos 2007, Gualtieri *et al* 2017). It should probably differ between sediment and buoyant particles such as plastics (Mathai *et al* 2015), and a size dependence should also be considered.

The second approach is the Lagrangian framework (see van Sebille *et al* 2018 for a recent review), which is commonly used in oceanography to analyse the three-dimensional transport of sea water (e.g. Drijfhout *et al* 1996, Blanke and Raynaud 1997, Döös *et al* 2008) and ocean dynamics (e.g. van Sebille *et al* 2012b, Ypma *et al* 2015). It is also the most commonly used framework to compute the pathways and distributions of plastic particles in the ocean (e.g. Lebreton *et al* 2012, Maes and Blanke 2015, Iwasaki *et al* 2017, Jalón-Rojas *et al* 2019, Onink *et al* 2019, van Gennip *et al* 2019). These Lagrangian simulations use (pre-computed) Eulerian velocity data derived from observations or models to compute the pathways of virtual particles, by integrating the (spatially- and temporarily-varying) velocity field in time. This is done with time integration, either using 'homebrew' codes or off-the-shelf community packages such as OceanParcels (Lange and van Sebille 2017, Delandmeter and van Sebille 2019), TrackMPD (Jalón-Rojas *et al* 2019), OpenDrift (Dagestad *et al* 2018), the Connectivity Modelling System (Paris *et al* 2013), Ariane (Blanke and Raynaud 1997, Durgadoo *et al* 2019), TRACMASS (Döös *et al* 2013) or PaTATO (Fredj *et al* 2016).

The three-dimensional motion of plastic particles in the ocean can be decomposed, somewhat arbitrarily, into a deterministic, or resolved, component and a turbulent, unresolved contribution. This unresolved contribution has to be modelled by stochastic terms in Lagrangian models. In the horizontal plane, mixing is often understood as the diffusive component in the advection equation, capturing the unresolved scales of the flow. Mesoscale and submesoscale eddy turbulence is often represented as a random walk in Lagrangian particle modelling (e.g. Haza *et al* 2012, Maximenko *et al* 2018, Lacerda *et al* 2019), where the turbulent diffusion coefficient has been assumed constant. However, this uniform turbulent diffusion will not be able to capture mixing in areas with varying eddy activity. Some studies have been carried out to determine the horizontal diffusion coefficient for specific regions (e.g. Zhurbas 2004, Rühs *et al* 2018), and it might be worthwhile to use this approach in simulations of plastic particle dispersion.

In the vertical direction, empirical parameterisations exist for the wind-driven mixing (Thorpe *et al* 2003), breaking waves (Kukulka and Brunner 2015), Langmuir cells (Brunner *et al* 2015), and the combination of winds, convection, and Langmuir cells (Harcourt 2012, 2014, Li *et al* 2016), as well as overturning transport by submesoscale mixed layer eddies (Fox-Kemper *et al* 2011) and symmetric instabilities (Bachman *et al* 2017). However, a variety of other types of frontal convergence and submesoscale phenomena such as intrusions and ramps remain to be parameterised. Furthermore, although breaking waves and the Langmuir cells play a key role in homogenizing currents and density in the ocean mixed boundary layer (Kukulka and Veron 2019), especially when the sea is fully developed (Li *et al* 2005), they are not routinely taken into account to correct sampling at sea.

Indeed, we often ignore the quantitative contribution of each of these processes in the vertical mixing and their coupling with plastic dynamics. In practical applications, drift simulations using even the best models often produce large discrepancies with observations (Potemra 2012, Maximenko *et al* 2018).

While Lagrangian models of virtual plastic particles have been widely used in open-ocean domains, their application to nearshore systems with complicated geometry are less mature (e.g. Yoon *et al* 2010, Neumann *et al* 2014, Critchell and Lambrechts 2016, Zhang 2017). Recently, it has been shown that the Lagrangian connectivity of nearshore flows depends strongly on the horizontal resolution of the underlying Eulerian hydrodynamic data (Dauhajre and McWilliams 2019). In particular, the simulation of beaching of virtual particles is mostly unexplored (Hinata *et al* 2017). Many Eulerian coastal flow models such as Delft3D (Lesser *et al* 2004) and X-Beach (Roelvink *et al* 2009) already include sediment transport; however, they are not ideal for simulating floating plastic because these models often do not adequately resolve surface processes such as wave breaking.

Because of the shallow water and high mixing levels, the interactions of both the hydrodynamics and the plastic particles with the seafloor and its sediments cannot be neglected within the surf and swash zone, even for positively buoyant particles. The boundary between the wet seafloor and dry beach is complex to model, although very important for the stranding probability of plastics.

Coastal flow models that resolve the fast and intermittent swash flow do exist (e.g. SWASH; see Zijlema *et al* 2011) but often do not fully resolve the surface dynamics and vertical flow components induced by wave breaking. This makes it difficult to capture the physical stranding and refloating of particles on the shoreline and the entrainment of particles under breaking waves. Although models like OpenFOAM (Weller *et al* 1998) and DualSPHysics (Crespo *et al* 2015) resolve wave breaking and particle-flow interaction (so could potentially give insight in the small-scale processes), computational power is still too limited to solve flow on a time scale longer than a few single wave events. Therefore, there is great potential to develop the combination of empirical parametrizations based on results from controlled laboratory experiments (for example: behaviour of plastic under breaking waves, or stranding of particles at dry beach) together with Lagrangian tracking of particles in numerical flow fields of coastal flow models.

7. Conclusions and discussion

Plastic litter in the ocean is an atrocity and a testament to our wasteful societies. At the same time, floating plastic debris is also a unique tracer and, as a result, might provide an opportunity to further improve our understanding of the physical laws and dynamics of the global ocean. In particular, the distribution of plastics may potentially be used to infer how suspended particles are transported by ocean flows across a wide range of spatial scales. In this review paper, we summarised the state of the art of our understanding of the physical processes controlling the transport and movement of plastics on the surface of the ocean. We have focused on *floating* plastic because that is the best-understood fraction of marine plastics, if not the largest fraction by weight. We have highlighted where knowledge gaps exist, and how field and laboratory measurements, remote sampling and numerical modelling can help to address these knowledge gaps.

Although the large majority of the literature on marine plastic debris is less than a decade old, much can be learned from more established fields and communities that work with other pollutants and particulate matter in the ocean such as oil, sediments, ice and plankton. The main hydrodynamical parameters such as terminal settling/rise velocity and critical shear velocity have been studied intensively in sedimentology, hydrology, hydrodynamics, etc. The effects of shape, density and size on these parameters were successfully parameterised in semi-empirical dependencies, which can also be applied to plastic particles. We therefore strongly encourage and invite these other communities to collaborate on marine debris studies to elucidate the processes that govern floating plastic debris transport.

Most of the discussion above has assumed a steady, non-changing ocean circulation. However, low-frequency variations, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), modify the ocean circulation and modulate the processes described in this paper, and trends associated with climate change can amplify some of these processes in the future. Winds and waves are expected to increase in a warmer atmosphere (Young and Ribal 2019), which will affect the vertical mixing of buoyant plastic particles. Western boundary currents and gyres are intensifying (Yang *et al* 2016), with implications for the large-scale transport of floating plastic. Higher-intensity storms could increase dispersion due to Stokes drift (e.g. Fraser *et al* 2018). Finally, sea level rise might affect coastal transport patterns and release large amounts of plastics trapped in coastal sediments or intermittently flooded urban areas (e.g. Axelsson and van Sebille 2017). While climate change potentially impacts plastic transport in several ways (through increased near-surface stratification, for example), the feedback of plastic pollution on climate change due to plastic degradation may also increase local emissions of the greenhouse gas methane, even though the global contribution may be small (Royer *et al* 2018).

The desire to know how currents move plastic around our seas and oceans is not only driven by our scientific curiosity. A risk assessment of the impacts of contamination by plastic debris on marine wildlife first requires an assessment of exposure, which is directly related to transport of debris from its sources (e.g. Hardesty and Wilcox 2017, Everaert *et al* 2018, Compa *et al* 2019). Effective and efficient coordination of mitigation measures of the plastic problem, such as plastic removal from beaches or from the ocean, requires accurate knowledge on how plastic is transported (Kataoka and Hinata 2015, Sherman and van Sebille 2016, De Frond *et al* 2019). Hence, further research into the physical oceanography of marine plastic debris will help inform the stakeholders and policy makers that aim to tackle one of today's most visible environmental problems.

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Data availability

No new data were created or analysed in this study.

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